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ELECTRICAL INSULATORS FOR THE
THETA-PINCH FUSION REACTOR

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INTRODUCTION

There are five major applications for electrical insulators in the Reference Theta-Pinch Reactor (RTPR):

first-wall insulator -- to stand off voltages generated during implosion heating

blanket intersegment insulator -- the continuation of the first-wall insulator along the sides of each segment to provide paths for magnetic flux penetration and to divide the implosion voltage

graphite-encapsulating insulator -- to reduce eddy-current losses in the blanket

implosion coil insulator -- to electrically separate magnet windings

compression coil insulator -- to electrically separate magnet windings.

The relationship of these insulators to the overall reactor design can be deduced by examination of Fig. 1. In this report the five applications listed above are described.

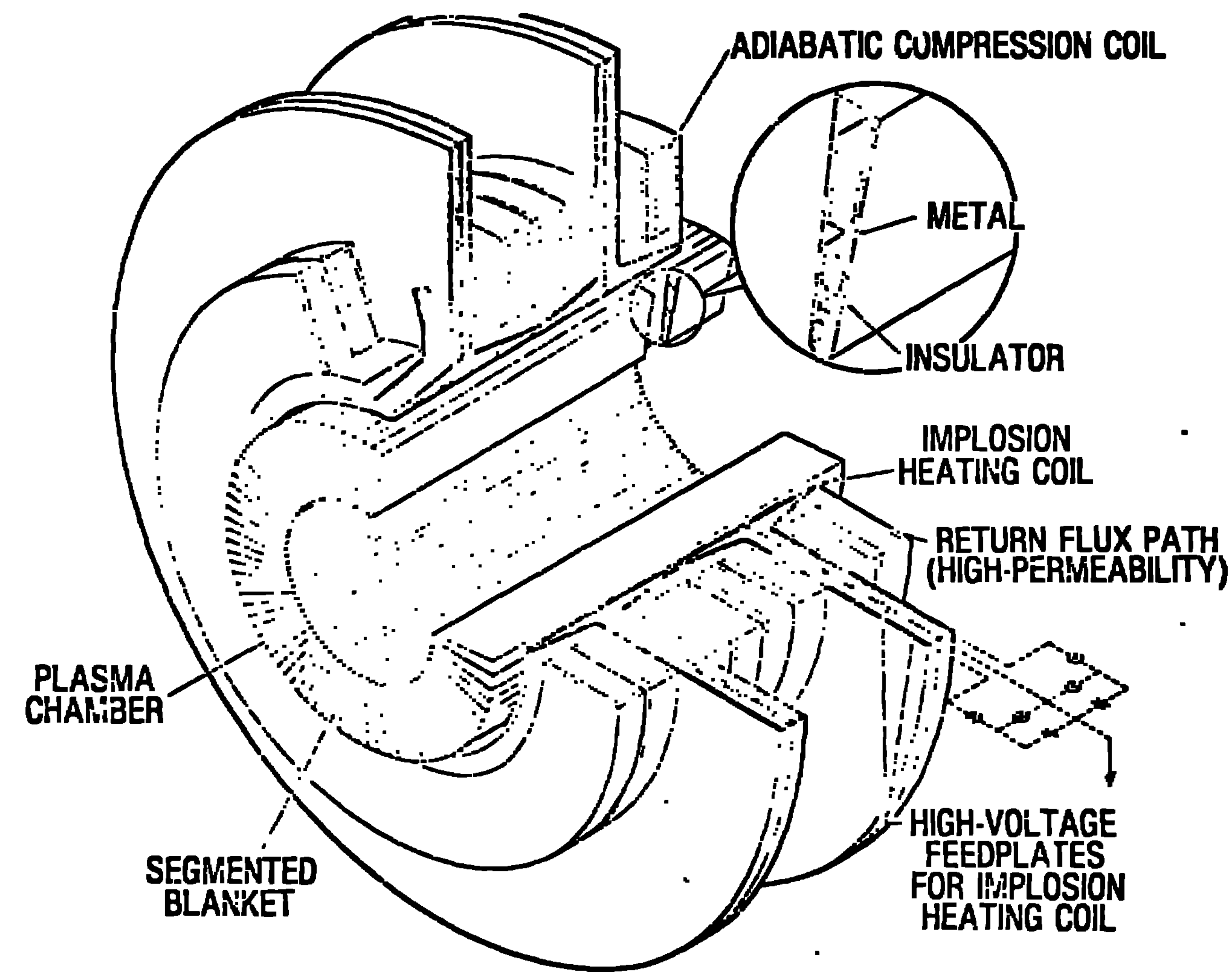

ADIABATIC COMPRESSION COIL
METAL
INSULATOR
IMPLOSION HEATING COIL
RETURN FLUX PATH (HIGH-PERMEABILITY)
PLASMA CHAMBER
SEGMENTED BLANKET
HIGH-VOLTAGE FEEDPLATES FOR IMPLOSION HEATING COIL

Fig. 1.

FIRST-WALL INSULATOR

Geometry

The original RTPR design calls for a 0.3-mm-thickness of Al_2O_3 bonded to 1 mm of Nb-1% Zr (Fig. 2). Subsequent designs have proposed a thin-insulator version (Fig. 3), a continuously-graded laminate (Fig. 4), a non-bonded system (Fig. 5), an all-ceramic first wall (Fig. 6), an all-ceramic segment (Fig. 7), and bumper protection (Fig. 8).

Operating Conditions

A. radiation fields

1. neutrons -- 8.1 x 10^{14} n/cm^2 sec (ave), ~8 x10^{16} n/cm^2 sec (peak), 2.5 x 10^{22} n/cm^2 yr

2. bremsstrahlung -- 72 J/cm^2 pulse

3. ionizing energy absorption rate in Al_2O_3 during burn -- 7 x 10^8 rad/sec

4. ionizing energy absorption rate in Al_2O_3 between burns -- ~ 2 x10^1 rad/sec

B. temperatures

The base operating temperature is ~1000 K. Temperature rises during a burn cycle for a number of first-wall designs are given in Table 1. In all cases but that of the bumper, temperatures return to the base value before the next pulse.

C. surrounding medium

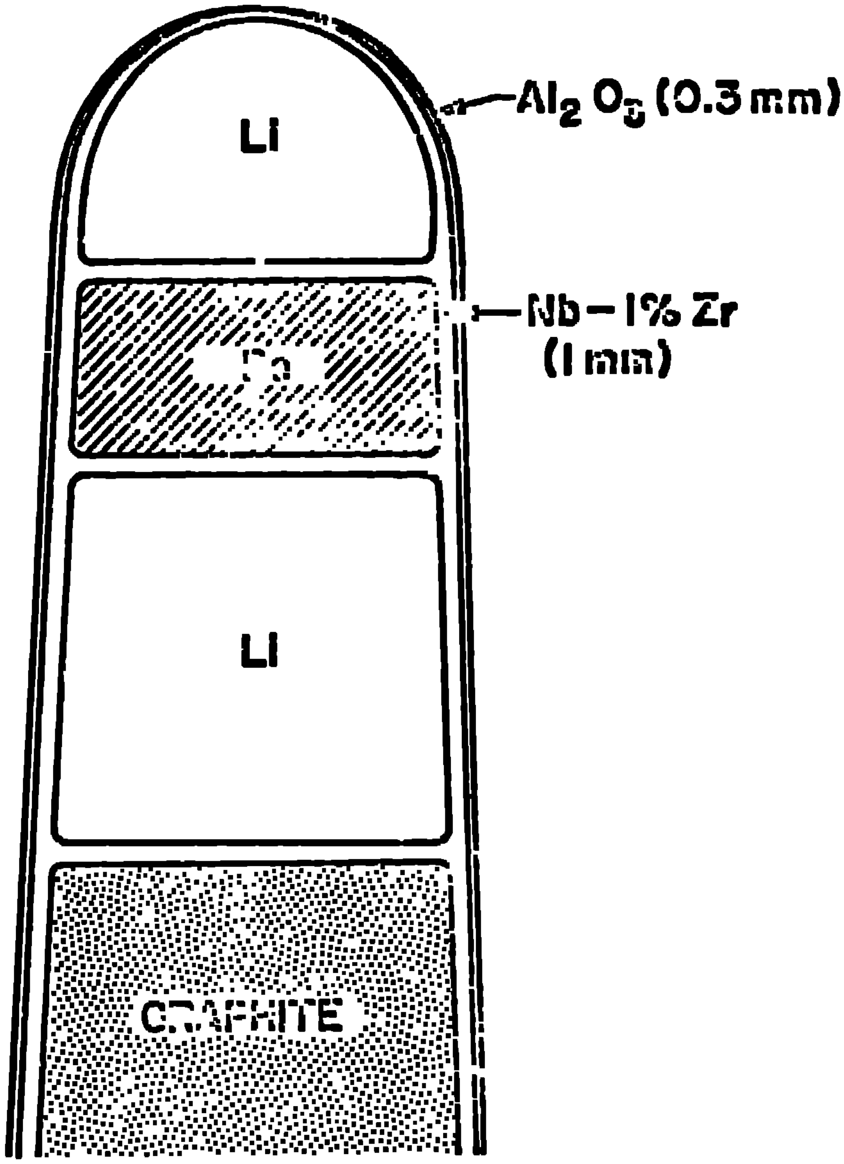
The inner surface will be exposed to D, T, and He particles, the energies of which will have been degraded by the neutral gas blanket. Particle energies, state of dissociation, and state of ionization have not been quantified. The outer surface will be in indirect contact with the blanket coolant (probably liquid lithium): the intervening material will be either a thick metal structure or a thin protective metallic layer.

D. stresses

Maximum thermally-induced tensile and compressive hoop stresses for a number of designs are given in Table I. These values were calculated by 1-D and 2-D finite element analyses. First-wall insulator stresses from sources other than thermal throughput have not been quantified.

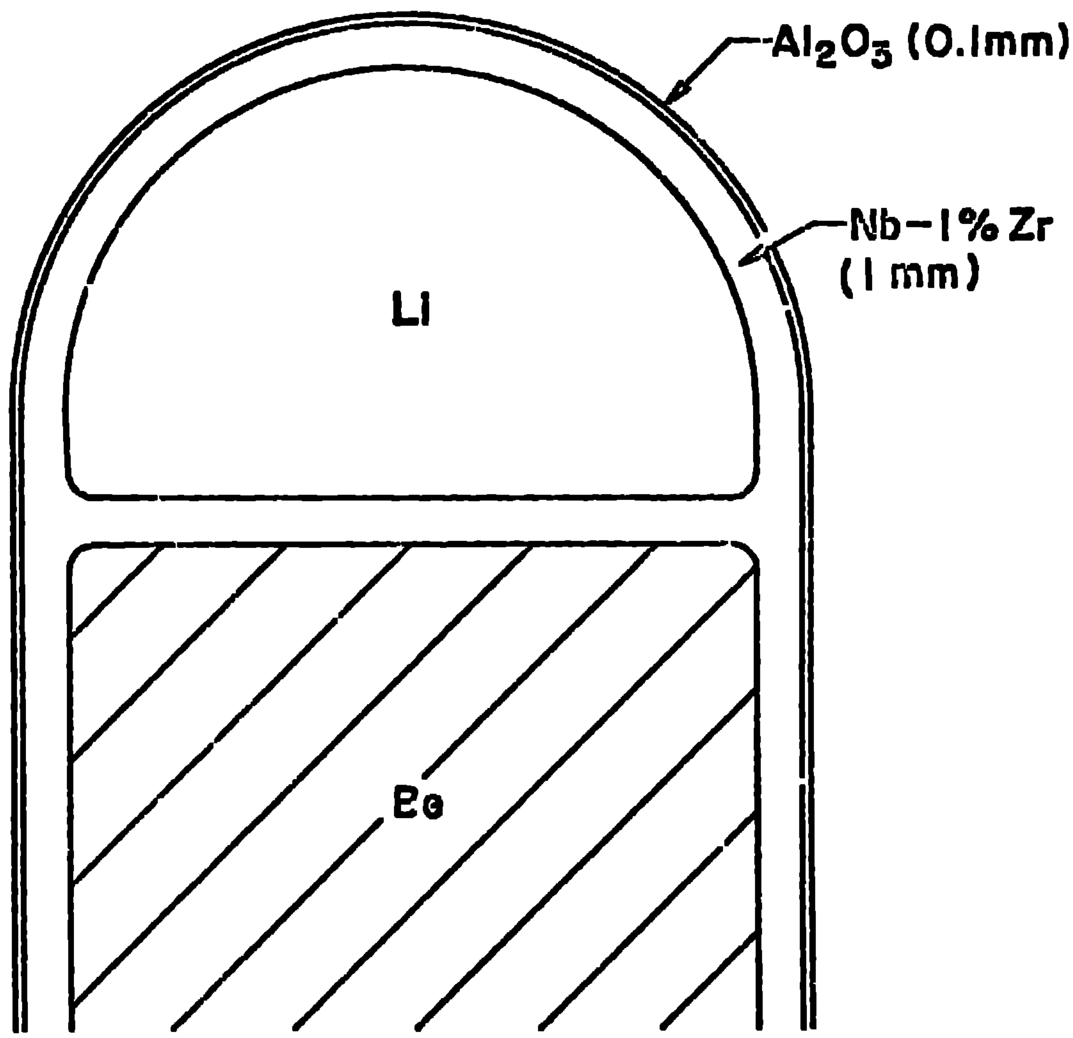
E. electrical requirements

1. surface dielectric strength -- 2 kV/cm (pulsed)
2. bulk dielectric strength -- 100 kV/cm (pulsed)
3. bulk resistivity -- not defined



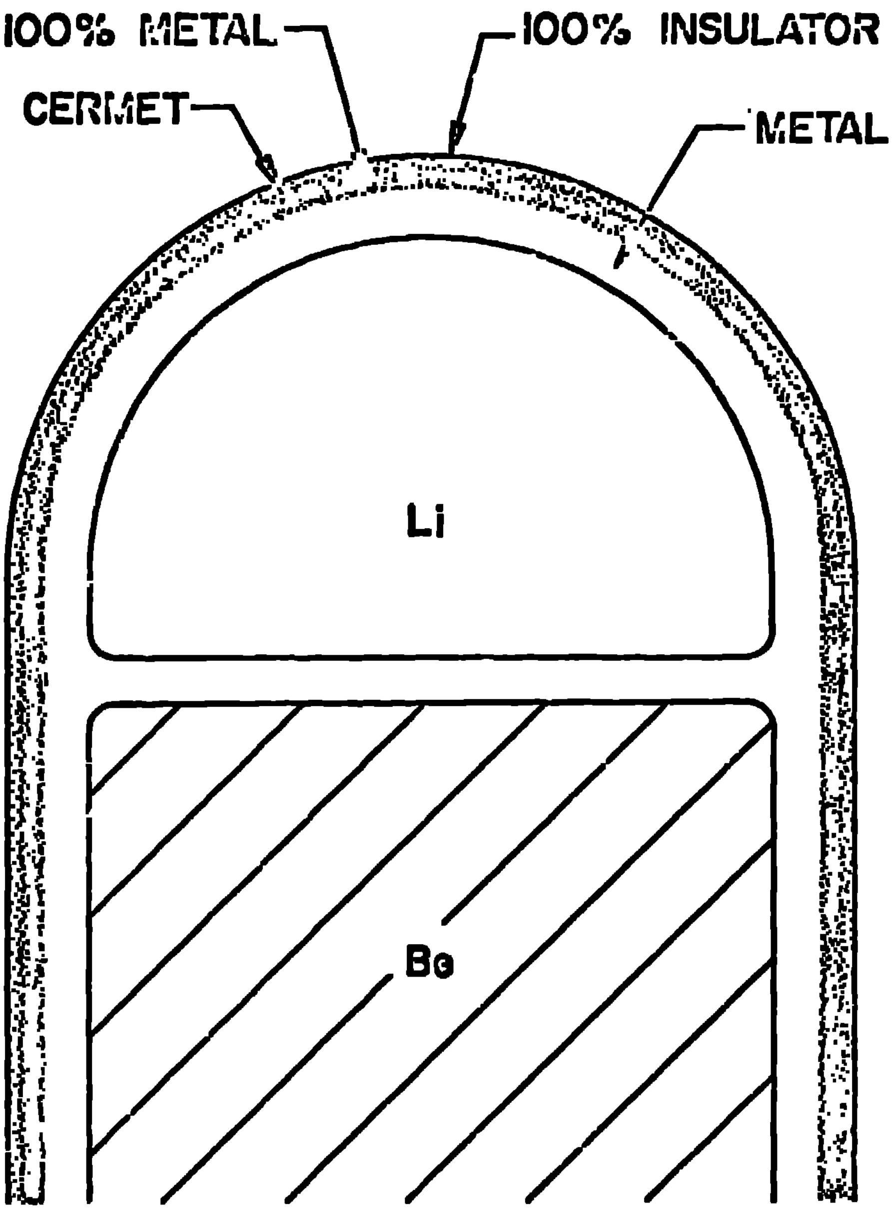
REFERENCE LAMINAR
DESIGN

Fig. 2.



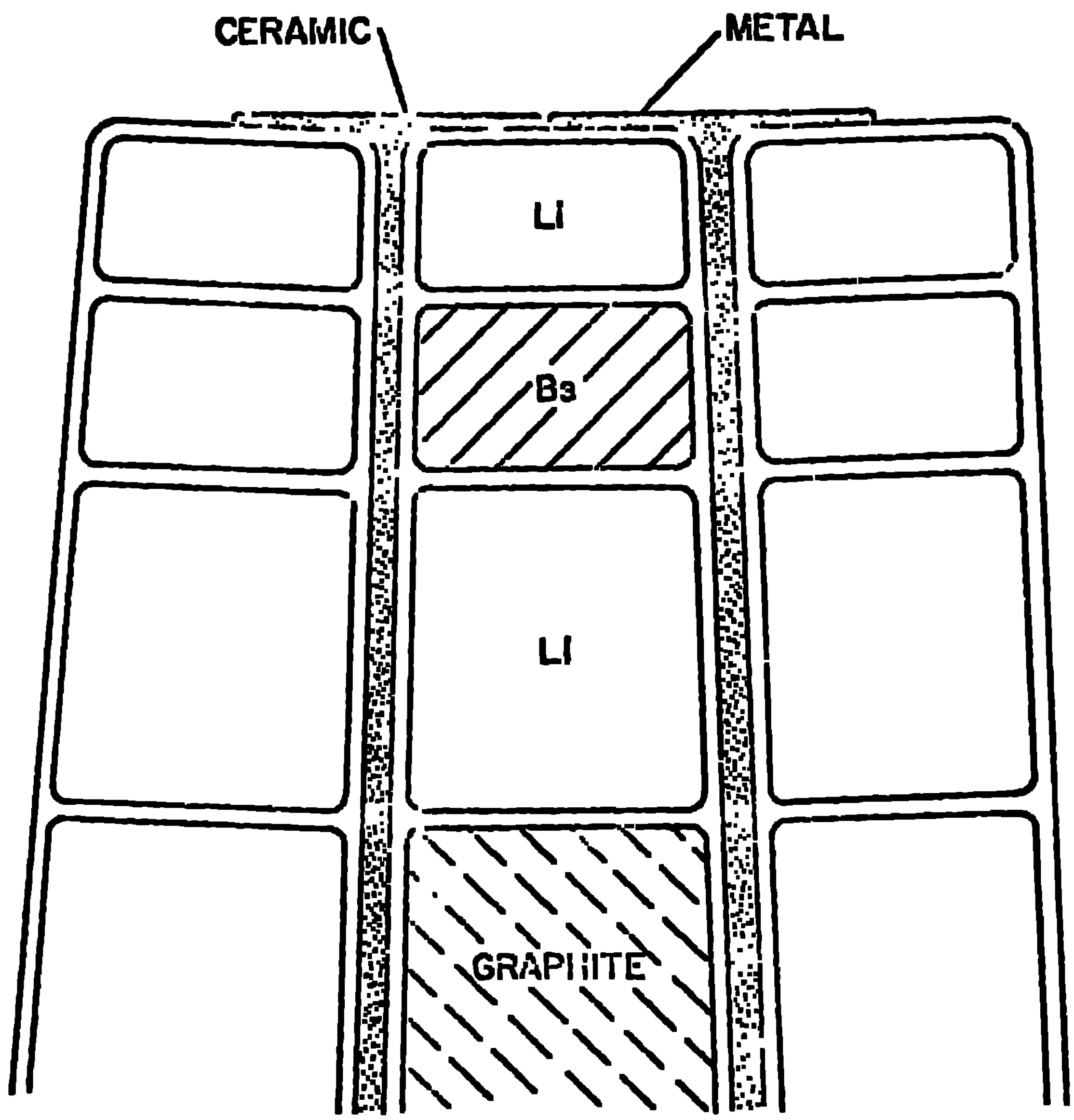
THIN-INSULATOR
LAMINAR DESIGN

Fig. 3.



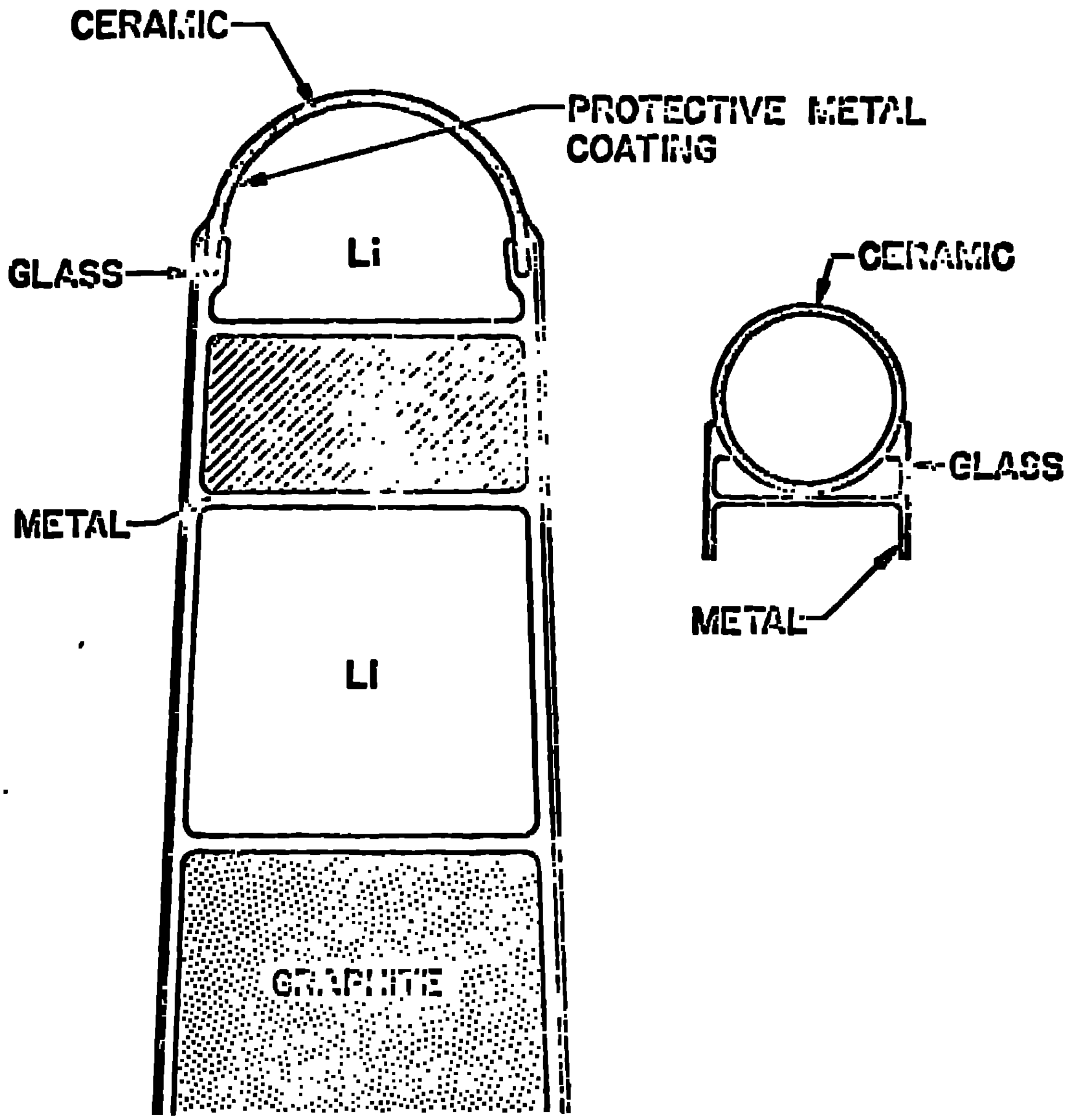
CONTINUOUSLY-GRADED
LAMINAR DESIGN

Fig. 4.



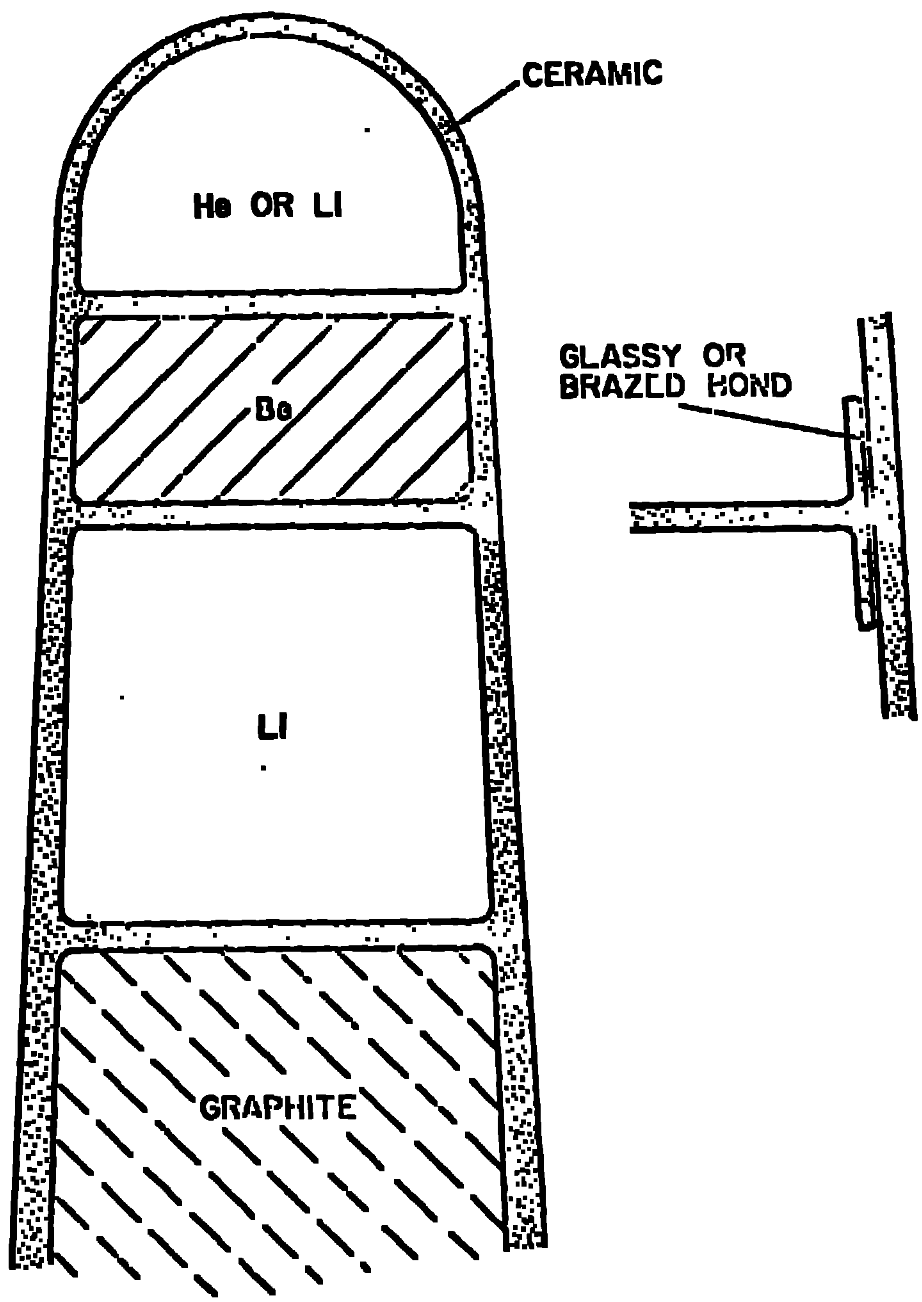
[illegible] INSULATOR DESIGN

Fig. 5.



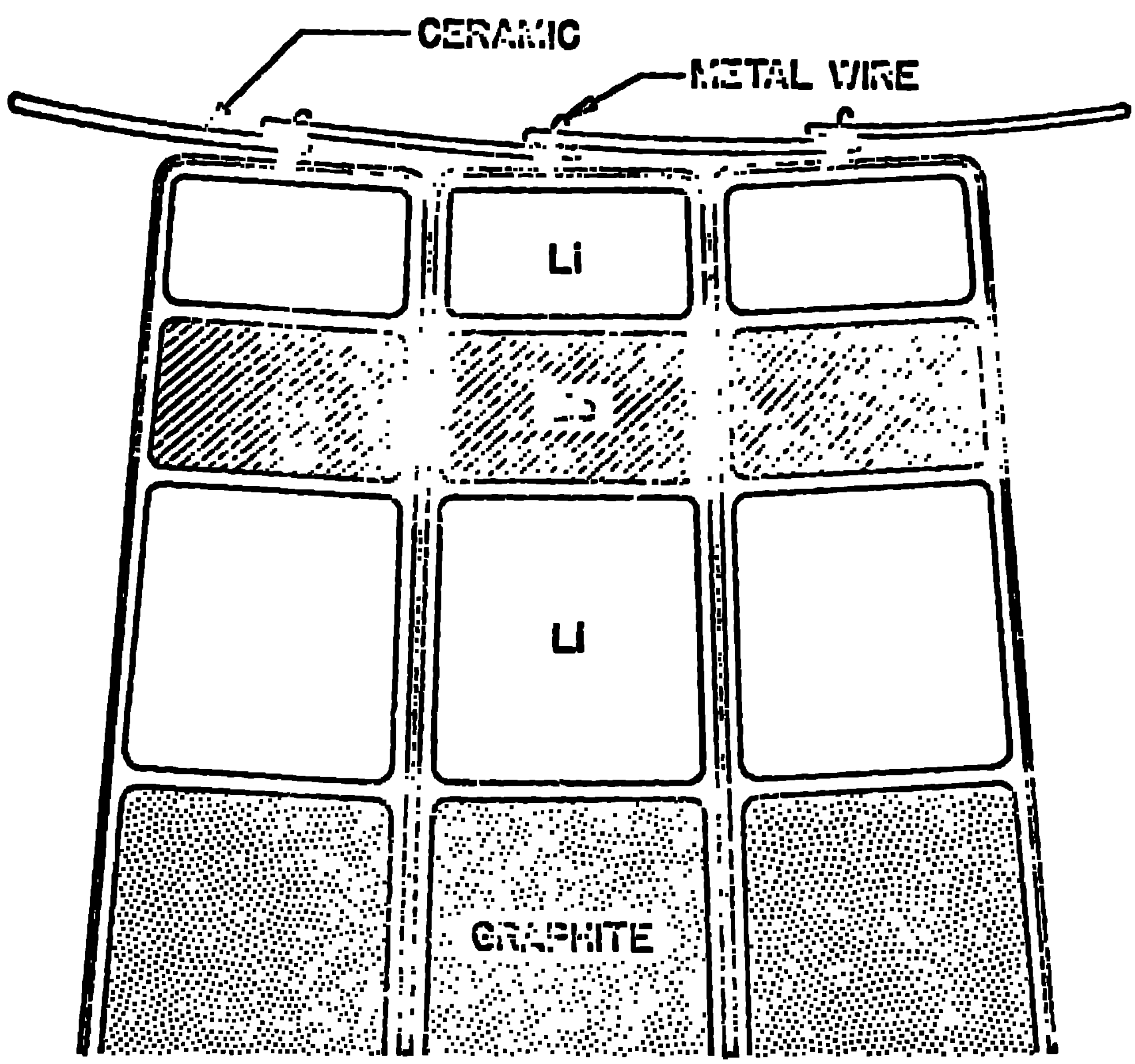
ALL-CERAMIC FIRST-WALL CONCEPT

Fig. 6.



All-Ceramic Segment Concept

Fig. 7.



BUMPER-PROTECTED
LAMINAR DESIGN

Fig. 8.

Table I.

RESULTS OF FIRST WALL INSULATOR PARAMETRIC STUDIES

DESIGN	TEMP. RISE, K*	MAX. TENSILE STRESS (STRENGTH), Pa x 10^{-8}	MAX. COMPR. STRESS (STRENGTH), Pa x 10^{-8}
LAMINAR (0.3 mm Al_2O_3)	326	1.50 (1.75)	6.60 (7)
LAMINAR (0.1 mm Al_2O_3)	312	0 (1.75)	3.90 (7)
BUMPER-PROTECTED 0.3 mm Al_2O_3 LAMINAR (1 mm Al_2O_3 BUMPER)	55	0.16 (1.75)	0.67 (7)
ALL-CERAMIC (5 mm Si_3N_4)	450	3.75 (7)	4.5 (>10)
BUMPER (1 mm SOLID Al_2O_3)	920		

*Base temperature assumed to be 1000K

F. lifetime

Although no definite lifetime requirement has been established, it would be highly desirable that the first-wall insulator remain operative until time for scheduled module maintenance (perhaps 2-5 years). At that time, segments with faulty first-wall insulator could be replaced or possibly repaired in-situ by a technique such as chemical vapor deposition.

Candidate Materials

It is premature to attempt to select candidate materials until sufficient data on long-term radiation effects are on hand. On the basis of preliminary studies, Si_3N_4, sialon, Si_2ON_2, $Y_3Al_5O_{12}$, $MgAl_2O_4$, ZrO_2, and Y_2O_3 look promising. The first three are strong and thermal-shock-resistant, and should at least initially exhibit good electrical properties. The latter two are not so good in structural and electrical behavior, but may be adequate. All seven show low swelling at ~1000 K when irradiated to ~3 DPA in EBR-II.

Estimate of the Magnitude of the Problems

A. material behavior

Knowledge of short-term behavior (e.g., electrical and mechanical effects) is adequate to allow tentative estimates of material performance. However, more data are needed to allow such estimates to be made with confidence. Long-term behavior cannot yet be predicted, primarily because of lack of information on radiation-induced structural changes (which affect both electrical and mechanical performance) and on chemical erosion. Fabrication and reactor operation variables are major uncertainties in the prediction of both short-term and long-term behavior, since they define the quality of the starting material and operating conditions.

A significant increase in effort (perhaps ten times that now available) is needed to supply answers to questions in the areas of electrical, structural, and chemical effects. The most critical task is proper simulation of high levels of fusion reactor-induced structural radiation damage.

In order to begin construction of an experimental power reactor (not ETPR) by 1985, choice of the first-wall insulator should be made by ~1981. A similar time schedule would be required for the other insulators described in this report.

B. fabrication

Techniques for fabrication of the first-wall insulator are receiving little attention today, but problems appear to be major. Work in this area should begin as soon as possible, so that studies can be carried out on insulators made by realistic fabrication methods. Effort should be put into extending fabrication state-of-the-art where necessary. Not only the insulator material, but techniques for its fabrication, must be ready by ~1981.

C. resource availability

Most insulators are made up of combinations of Si, Al, Mg, O, and N, all of which are plentiful. If such materials as Y_2O_3 and ZrO_2 become serious contenders, the availability of the metallic constituents should be considered.

Dependence of Insulator Requirements on Reactor Design and Operating Parameters

First-wall insulator requirements are strongly tied to reactor characteristics. Some of these are:

duty factor
burn duration
implosion heating voltage
first-wall design
number of segments per module (now 100)
maintenance schedules
uniformity of wall loading
gas blanket behavior.

The first-wall insulator can be fully developed only after those reactor parameters which affect the insulator are completely specified.

BLANKET INTERSEGMENT INSULATOR

Geometry

The original RTPR design called for a 0.3-mm-thick insulating layer bonded to the Nb-1% Zr sides of each segment. Free-standing plates with attached first-wall insulators are also under consideration (Fig. 5). With an all-ceramic design, the intersegment insulator is part of the segment structure (Fig. 7).

Operating Conditions

A. radiation fields

1. neutrons -- ~8×10^{14} n/cm^2 sec (ave) at innermost region, ~6×10^{13} n/cm^2 sec (ave) at outermost region.

2. ionizing energy absorption rate in Al_2O_3 during burn -- ~2×10^7 rad/sec (innermost)

3. ionizing energy absorption rate in Al_2O_3 between burns -- ~2×10^4 rad/sec (innermost)

B. temperatures

The initial base operating temperature is ~1000 K; this rises ~100 K during achievement of steady-state conditions. Temperature gradient across the intersegment insulator is less than that across the first wall.

C. surrounding medium

The outer surface will be in contact with low-pressure D-T gas (~10 mTorr). The inner surface will be either bonded to, or in mechanical contact with, the segment structure or contents. With an all-ceramic segment design, a thin protective metallic layer may be required on the inner surface.

D. stresses

Intersegment insulator stresses have not been calculated, but are thought to be lower than those imposed on the first wall.

E. electrical requirements

1. bulk dielectric strength -- 100 kV/cm (pulsed)

2. bulk resistivity -- >10^3 Ω-cm (pulsed)

3. surface dielectric strength -- not defined

F. lifetime

Although no definite lifetime requirement has been established, it would be highly desirable that the intersegment insulator remain operative until time for scheduled module maintanence (perhaps 2-5 years).

Candidate Materials

The comments on candidate materials in the section on the first-wall insulattor are generally applicable here. Since strength and thermal shock resistance requirements are expected to be lower for the intersegment insulator, a wider variety of materials, including glasses, can be considered.

Estimate of the Magnitude of the Problems

Comments in the section on the first-wall insulator are applicable here. In general, results from first-wall insulator studies could be used to develop the intersegment insulator. In some specific areas (e.g., effect of cracking on reactor performance), separate investigations might be required.

Dependence of Insulator Requirements on Reactor Design and Operating Parameters

Remarks on this subject in the secion on the first-wall insulator are generally applicable here.

GRAPHITE-ENCAPSULATING INSULATOR

Geometry

The two graphite "logs" in each segment of the RTPR are canned in a laminate of 1 mm Nb, 0.3 mm Al_2O_3, and 1 mm Nb.

Operating Conditions

A. radiation fields

1. neutrons -- $\sim 6 \times 10^{14}$ n/cm^2 sec (ave) at innermost region, $\sim 8 \times 10^{13}$ n/cm^2 sec (ave) at outermost region.

2. ionizing energy absorption rate in Al_2O_3 during burn -- $\sim 1 \times 10^7$ rad/sec (innermost)

3. ionizing energy absorption rate in Al_2O_3 between burns -- $\sim 1 \times 10^4$ rad/sec (innermost)

B. temperatures

Comments in the section on the blanket intersegment insulator are generally applicable here.

C. surrounding medium

The insulator is metal-clad.

D. stresses

Stresses for the encapsulating insulator have not been calculated, but are expected to be large if differential swelling of graphite or niobium is significant.

E. electrical requirements

1. bulk dielectric strength -- small (DC)

2. bulk resistivity -- not defined

F. lifetime

The comments on lifetime in the section on the intersegment insulator are generally applicable here. Graphite "logs" and the encapsulating insulator would be replaced as a unit.

Candidate Materials

The comments on candidate materials in the section on the first wall insulator are generally applicable here. For this low voltage DC application, an insulator resistant to polarization (ion migration) is needed. A glassy insulator which could deform to accommodate swelling stresses might be utilized.

Estimate of the Magnitude of the Problems

Comments in the section on the first-wall insulator are applicable here. In general, results from first-wall insulator studies could be used to develop the encapsulating insulator. However, special requirements such as those just mentioned must be considered separately.

Dependence of Insulator Requirements on Reactor Design and Operating Parameters

Encapsulating insulator requirements are dependent on details of blanket design, material choices, and maintenance schedules. These must be fully defined before a final choice for this insulator can be made.

IMPLOSION COIL INSULATOR

Geometry

The implosion coil is made up of a number of ceramic bodies of a "top hat" configuration, stacked end to end. Ribbon-type electrical leads are bonded to the surface of each body and covered with ceramic or glass to suppress surface tracking.

Operating Conditions

A. radiation fields

1. neutrons -- $\sim 6 \times 10^{13}$ n/cm^2 sec (ave)

2. ionizing energy absorption rate in Al_2O_3 during burn -- $\sim 4 \times 10^6$ rad/sec (innermost)

3. ionizing energy absorption rate in Al_2O_3 between burns -- $\sim 4 \times 10^3$ rad/sec (innermost)

B. temperatures

The implosion coil is thermally insulated from the blanket and is gas-cooled; it will operate near room temperature.

C. surrounding medium

The implosion coil will be in a nominal vacuum environment.

D. stresses

Moderate stresses from magnetic field effects are expected.

E. electrical requirements

1. bulk dielectric strength -- 100 kV/cm (pulsed)

F. lifetime

No definite lifetime requirement has been set. It is anticipated that the implosion coil will have a longer lifetime than will other components of a module.

Candidate Materials

No insulator studies have been conducted to date for this application. It is anticipated that a number of ceramics will be able to meet the electrical and structural requirements and show adequate resistance to the moderate radiation fields.

Estimate of the Magnitude of the Problems

A. material behavior

It is anticipated that only a modest amount of R & D will be required to develop materials for this application.

B. fabrication

Fabrication problems will be non-trivial, but appear to be resolvable.

C. resource availability

Comments on this topic for the first-wall insulator are applicable here.

Dependence of Insulator Requirements on Reactor Design and Operating Parameters

Implosion coil insulator electrical requirements depend on the desired characteristics of the implosion heating system, which are still under study.

COMPRESSION COIL INSULATOR

Geometry

The coil is made up of windings of Cu-Zr alloy interleaved with ceramic insulator (mechanical contact). The insulator may be in either bulk or fabric form.

Operating Conditions

A. radiation fields

1. neutrons -- from $\sim 5 \times 10^{13}$ n/cm^2 sec (ave) at innermost location to $\sim 8 \times 10^{11}$ n/cm^2 sec (ave) at outermost location
2. ionizing energy absorption rate in Al_2O_3 during burn -- $\sim 2 \times 10^6$ rad/sec (innermost)
3. ionizing energy absorption rate in Al_2O_3 between burns -- $\sim 2 \times 10^3$ rad/sec (innermost)

B. temperatures

The coil will be liquid-cooled, and operate near room temperature.

C. surrounding medium

The insulator will be in contact with the conductor and the liquid coolant (the latter not yet specified).

D. stresses

Insulator stresses have not yet been calculated, but could be high. Magnet design should be chosen to minimize such stresses.

E. electrical requirements

Dielectric strength required is a function of magnet design, which has not yet been fixed. However, electric fields are expected to be small.

F. lifetime

The compression coil should last ~ 20 years.

Candidate Materials

No insulator studies have been conducted to date for this application. It is anticipated that a number of ceramics will be able to meet the strength requirements, given proper magnet design, and show adequate resistance to the moderate radiation fields. Electrical requirements are modest.

Estimate of the Magnitude of the Problems

A. material behavior

It is anticipated that only a modest amount of R & D will be required to develop materials for this application.

B. fabrication

No major fabrication problems are anticipated for this insulator.

C. resource availability

Comments on this topic for the first-wall insulator are applicable here.

Dependence of Insulator Requirements on Reactor Design and Operating Parameters

The compression coil insulator strength requirement is strongly dependent on the mechanical design of the coil, and on magnetic field strength desired.